Juvenile Yearling Chinook Salmon Survival in the Columbia River Plume (USA): An Information-theoretic Evaluation of Environmental Factors with Telemetry Data

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Pearcy (1992) suggested that the number of juvenile salmon that return as adults may be established during a 'critical period' of early marine survival. To best identify the processes directly affecting early marine survival, it is necessary to first measure juvenile survival directly, which is now possible with acoustic telemetry technology (Rechisky et al. 2009; Moore et al. 2010; Melnychuk et al. 2011; Welch et al. 2011; Thorstad et al. 2012). Our first objective was to evaluate the ability of a simple exponential decay model to describe survival data for tagged yearling Chinook salmon in the Columbia River plume. Our second objective was to evaluate the influence of environmental processes and we used model residuals to examine whether measures of biological productivity or total dissolved gas levels in the river would add additional predictive power to the exponential decay model (Kutner et al. 2005). Finally, given the interest in manipulating the dynamics of the Columbia River plume (through flow-controlled river discharge) to benefit juvenile salmon, we used the Akaike information criterion (AIC) for model selection to examine three factors that may affect plume residence time, including sea surface temperature, which may influence the timing and speed of migration, and upwelling and river discharge, which are related to plume orientation and local currents encountered by migrating salmon (Brett et al. 1958; Burnham and Anderson 2002; Sykes and Shrimpton 2010; Burla et al. 2010a, b; Jacobson et al. 2012; Martin et al. 2012).
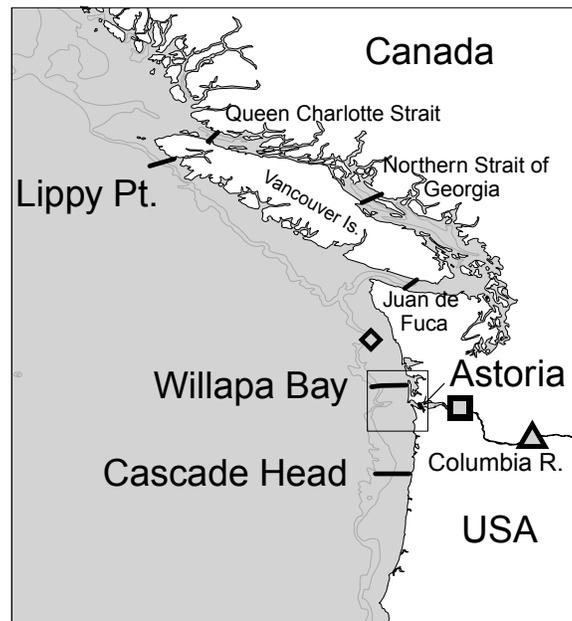

Fig. 1. Map of the study region; the box encompassing the Willapa and Astoria sub-arrays delineates the Columbia River plume area. The black lines mark the named telemetry sub-arrays. Data collection sites include NOAA buoy 46041 (diamond), Beaver Army Terminal at Quincy, OR (square), and Bonneville Dam/Camas Washougal (triangle).

Between 2008 and 2011, 4,646 yearling Chinook salmon from the Columbia River basin were surgically implanted with uniquely coded acoustic transmitters and then tracked as they migrated down the Columbia River and north along the continental shelf (Fig. 1). Tagged fish were grouped according to their origin and handling and included Columbia River run-of-the-river (CR) groups, Snake River run-of the-river (SR) groups, and Snake River Transport (ST) groups. Detection data from lines of acoustic receivers (sub-arrays) that bisected the river and continental shelf at locations extending from

the Snake River to Lippy Point, British Columbia, Canada (Fig. 1), were used to estimate apparent survival for each group to each detection line in each year in a special case of the Cormack-Jolly-Seber (CJS) live-recapture modeling framework (Lebreton et al. 1992). Modeling was implemented in program MARK (White and Burnham 1999). The complete details of methods, surgical protocols, release locations and timing, tag effect studies, and array efficiency can be found in Porter et al. (2009a, b, 2010, 2011, 2012a and 2012b) and Rechisky and Welch (2010). We excluded a group of transported fish released in early-April 2009 that was released much earlier in the season than the remaining groups, displayed very different migratory behaviors, and likely entered the plume before predators became abundant (Porter et al. 2009b; Collis et al. 2002; Emmett et al. 2006).

Survival data for the Columbia River plume region between the lines of receivers at the Astoria Bridge and Willapa Bay were fit to a simple exponential decay model using the nls function in R (R Development Core Team 2011),

$$S_P = e^{-k \cdot T_P}$$

where S_P is plume survival, k is the mortality rate constant, e^{-k} is the apparent daily survival rate, and T_P is median plume residence time. T_P was determined by subtracting the median individual final detections at Astoria (i.e., plume entry time) from the median of the final detections at Willapa Bay (plume departure). We also estimated plume survival in 2006, when there was no sub-array at Astoria, by dividing the 2006 estimates of combined lower river/plume survival (Bonneville Dam to Willapa Bay) by the average lower river survival (Bonneville Dam to Astoria) in 2008-2011 (average=0.85) and used the range of lower river survival from 2008-2011 (0.71 to 0.99; Porter et al. 2012a) to estimate a 2006 maximum and minimum plume survival.

We plotted logit-transformed survival and residuals from the exponential decay model against the timing of the biological spring transition, two- and four-week cumulative upwelling, and gas supersaturation in the lower river to evaluate the potential role of biological productivity and river conditions on plume survival (Kutner et al. 2005). We also calculated the coefficients of determination (R-squared) between logit-transformed survival and each of the variables.

Environmental data were obtained from public databases. Upwelling index values at 48°N (cubic meters/second/100 meters coastline) were obtained from the NOAA Pacific Fisheries Environmental Laboratory at http://www.pfeg.noaa.gov/. Biological spring transition dates for 2008-2011 and lower river gas saturation data were obtained through the Columbia River data access in real time (DART) site at http://www.cbr.washington.edu/dart/. Transition dates were used with the permission of Dr. William T. Peterson (NOAA Northwest Fisheries Science Center). Sea surface temperature (SST °C) data from NOAA data buoy 46041 (Fig. 1), which had a complete data set for periods when tagged juvenile salmon were transiting the plume, were obtained from http://www.ndbc.noaa.gov/. River discharge recorded at Beaver Army Terminal was extracted from the USACE National Water Information System at http://waterdata.usgs.gov/.

We evaluated the environmental factors potentially governing plume residence time by comparing the AIC weights and evidence ratios of a global model of plume residence time, $T_P \sim SST+UP+DIS+UP:DIS$, and its 8 sub-model combinations (Table 1), where T_P is plume residence time, *SST* is sea surface temperature, *UP* is upwelling, and *DIS* is river discharge. Modeling was conducted in R with package MuMIn (Burnham and Anderson 2002; Johnson and Omland 2004; Kutner et al. 2005; Bartoń 2012).

Table 1. Summary of model selection statistics. Evidence is a measure of how many times less likely the model is the best model relative to the top ranked model.

Model	Intercept Parameter	SST Parameter	Upwelling Parameter	Discharge Parameter	Disch:Up Parameter	AICc	ΔAICc	Model Weight	Evidence
SST	29.06	-1.735	-	-	-	41.77295	0	.92	1.0
SST+Dis	27.83	-1.716	-	0.0007817	-	48.80734	7.034388	.027	33.7
SST+Up	29.12	-1.740	0.0009444	-	-	48.97223	7.199273	.025	36.6
Up	8.228	-	-0.0531	-	-	50. 24660	8.473644	.013	69.2
Dis	5.966	-	-	0.0001642	-	51.00925	9.236294	.0091	101.3
Up+Dis	1.838	-	-0.1010	0.0005078	-	55.36579	13.592843	.0010	894.6
SST+Up+Dis	25.89	-1.615	-0.01588	0.0001372	-	60.69276	18.919811	.000071	12834.7
Up*Dis	-2.11	-	-0.6625	0.0006881	0.00005825	65.05639	23.283434	.0000081	113745.3
SST+Up*Dis	22.15	-1.447	-0.2014	0.0002325	0.00001833	84.37098	42.598007	.0000000052	1778441824.7

Results showed there was no evidence of any violation of non-linear model assumptions in the exponential decay model, but the model performed better for run-of-the-river migrant groups than groups transported and released below Bonneville Dam (Fig. 2). Derived survival data from 2006 matches the model pattern and refitting the exponential decay model with the 2006 data only changed the decay constant (daily mortality) slightly, from 0.12 to 0.11. In-river migrants entered the plume in a more continuous fashion than transported fish; the median absolute deviation from the median plume entry date of transported juveniles was less than one day (mean=0.56 day), but ranged from 1-7 days (mean=3.39 days) for the in-river migrants. Due to the high variability in transport group survival, we evaluated environmental influences and plume residence time models using the in-river groups only. There were no strong patterns in the plots of the model residuals against biological spring transition dates, two- and four-week cumulative upwelling, or gas supersaturation to suggest that incorporating them would improve the model, nor was there any apparent relationship with survival (R-squared values were 0.14, 0.02, 0.01, and 0.13, respectively). Among the nine candidate models for predicting plume residence time, the model containing only sea surface temperature outperformed all others, as measured by AICc distance and model weights (weight = 92%; Table 1). There was no evidence in diagnostic plots that the SST model violated any standard linear model assumptions.
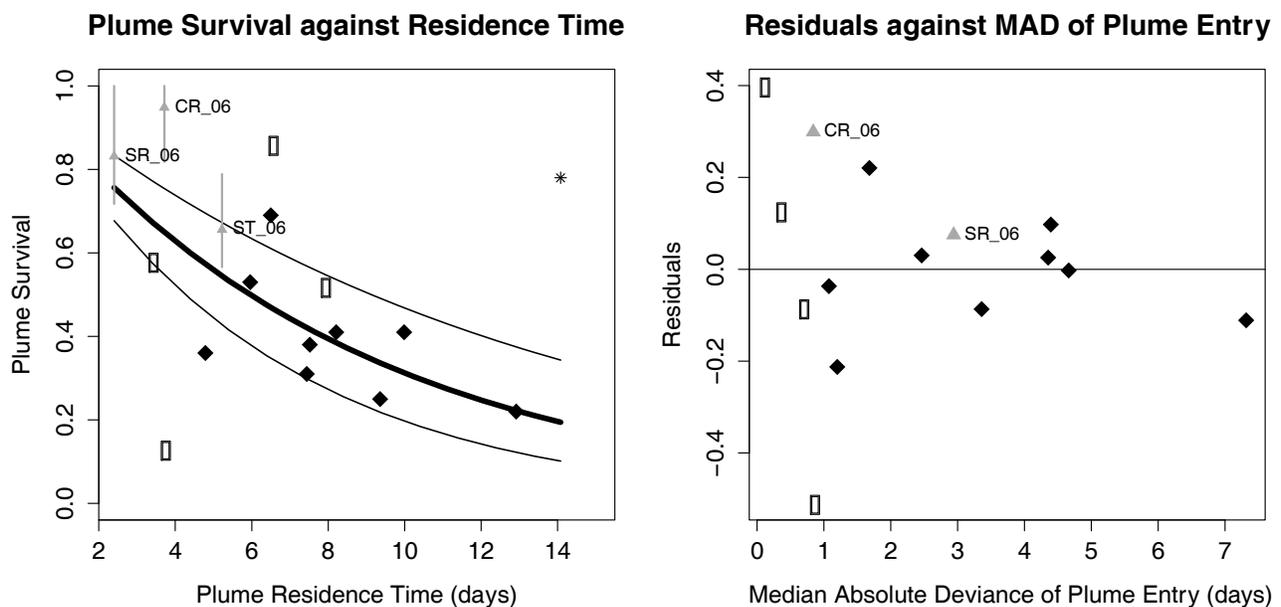

Fig. 2. (Left panel) Comparison of Columbia River plume survival with plume residence time showing the regression curve (thick line) and 95% confidence intervals (thin lines). The model clearly fits the in-river migrant groups (diamonds) better than transported groups (open rectangles). Derived estimates of 2006 plume survival and residence time (triangles; vertical lines show maximum and minimum estimates) also fit the pattern of a simple exponential decline in survival with residence time. The excluded 2009 early-release transport group is also shown (star). (Right panel) Residuals from the regression relationship exhibit greater variance when the spread in plume entry times is low (measured by median absolute deviation), as is also the case for all of the transported groups (open rectangles) in this study. Median absolute deviation at the Bonneville dam sub-array is shown for 2006 (triangles); there are no data for the 2006 transport group as they were released in the vicinity of Bonneville sub-array.

In conclusion, a simple exponential decay model describes juvenile yearling Chinook salmon plume survival well, although the model performs best when analysis is restricted to groups of fish whose individuals enter the plume over a longer time period (Fig. 2). Cohesion in the timing of plume entry in transport groups may mean that a chance encounter with aggregated predators would disproportionately affect overall survival relative to more dispersed groups. This may explain the greater variability in the survival of transported groups and thus the poorer model fit (Fig. 2). The derived estimates of 2006 plume survival lend additional support to the idea that plume survival is negatively related to travel time. We believe that plume residence times (average 7.3 days) were too short for starvation to have had an effect and that predation was the most likely cause of plume mortality (Methot and Dorn 1995; Collis et al. 2002; Lyons et al. 2005; Agostini et al. 2006; Emmett et al. 2006). Plume survival does not appear to be related to biological productivity measures, but there may be a weak effect of exposure to total dissolved gas levels near 125% in the lower Columbia River (a possibility we are exploring in a separate analysis).

While it appears that higher yearling Chinook salmon plume survival could be obtained by reducing residence time, the best model of plume residence time includes only sea surface temperature, which suggests that improving plume survival is beyond management control. Models that included upwelling or river discharge (which can be influenced by management action) had little weight, which is consistent with Burla et al. (2010a) who found that the physical dynamics of the plume at the time of ocean entry do not affect fish survival.

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